OCEANICS INC.

DEVELOPMENT AND TESTING OF AN AIRCRAFT CARRIER DECK MOTION PREDICTION SYSTEM

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Oceanics, Inc.
Plainview, New York

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OCEANICS INC.

ABSTRACT

The elements, both hardware and software, entering into the establishment of a system aboard ship for testing a concept for aircraft carrier deck motion prediction are described. The test procedures and results experienced in full scale evaluation are also presented. Due to lack of sufficiently severe environmental wave disturbances in some cases, as well as limited operational speed characteristics of the ship in other cases, the information obtained during the full scale tests was not suitable for proper evaluation of the motion prediction technique. The major source of difficulty encountered in the situation with sufficiently severe ocean waves was interference due to ship-generated waves, which would be overcome by having a forward speed of 10 kts. or greater. All aspects of data processing necessary in this program functioned properly, and a proposed method of wave motion prediction was shown to be successful. Further full scale testing under conditions with significant ship motions while the carrier has sufficiently high speed is recommended for complete evaluation of the prediction technique.

TABLE OF CONTENTS

Page No.

Abstract.. ii

Table of Contents..................................... iii

Nomenclature.. iv

INTRODUCTION.. 1

GENERAL DESCRIPTION OF ELEMENTS COMPRISING SYSTEM....... 4

WAVE MEASURING SYSTEM................................. 6

SHIP MOTION RECORDING SYSTEM.......................... 9

COMPUTER SYSTEM AND COMPUTATIONAL REQUIREMENTS.......... 14

SHIPBOARD INSTALLATION AND TEST CONDITIONS.............. 25

DISCUSSION AND ANALYSIS OF TEST RESULTS................. 27

CONCLUSIONS AND RECOMMENDATIONS......................... 37

REFERENCES.. 39

Figures 1 through 13 Following Page 40

NOMENCLATURE

Symbol	Description
a	Amplitude of surface wave elevation
g	Acceleration due to gravity
h_b	Vertical displacement of wave height sensor
$K_z(t), K_\theta(t)$	Kernel functions for heave and pitch, respectively
n	White noise signal input
s	Sensor signal output; also Laplace transform operator
T	Prediction time
$T_{z\eta}$, $T_{\theta\eta}$	Response operator (amplitude and phase relative to wave) for heave and pitch, respectively
t	Time
V	Forward speed
x_1	x-coordinate location of wave measurement point
z	Ship heave motion, positive upward
ζ	Damping parameter in transfer functions
η	Wave elevation measured ahead of bow
$\hat{\eta}$	Wave elevation estimate
θ	Pitch angle, positive bow down
τ_e	Effective time extent of kernel function
Φ	State transition matrix
ϕ_z, ϕ_θ	Phase angles of heave and pitch, respectively, with regard to wave reference
ω_e	Circular frequency of encounter (rad./sec.)
ω_n	Central frequency of power spectrum (rad./sec.)

DEVELOPMENT AND TESTING OF AN AIRCRAFT CARRIER

DECK MOTION PREDICTION SYSTEM

INTRODUCTION

Analytical work has been carried out under Office of Naval Research Contract No. Nonr-4186(00) at Oceanics, Inc. on the subject of aircraft carrier ship motions at sea [1], with the main intent to provide information on motion characteristics of carriers for utilization in a computer study of the aircraft carrier landing process [2]. The results of this first study [1] were various motion magnitudes and phases for heave, pitch and roll motions of a FORRESTAL class carrier, together with the overall motion characteristics in the form of power spectra for different sea states. In addition, as a continuation of the initial task, a study was made of the ability to provide a continuous prediction of the time history of the carrier motions in an irregular sea, and the results were presented in [3]. The output of this prediction study, which was based on an extension of analytical techniques and comparison of the results with model test records from wave towing tanks, showed very good success of the prediction technique. It was possible to predict motions in seas corresponding to Sea State 6, with the carrier at forward speeds of 20 and 30 knots, for a prediction time of about six (6) seconds. Other techniques for increasing this prediction time were also outlined in [3], although not directly applied in this initial program, but means of implementation of this additional time increment of prediction are readily available.

The technique that was proven successful in model scale tests is based upon measurement of the waves just ahead of the bow of the carrier, and processing this data by use of a computer to present the continuous predicted time history of the carrier motion. The actual implementation and use of this prediction information in the aircraft carrier landing operation was not considered in detail as part of the work, but various means are envisioned for its direct application; viz.

1) as an auxiliary aid to the LSO to determine wave-off conditions or final command inputs; or
2) as a means of altering the orientation of the FLOLS beam for the recommended final glide path slope to effect a successful landing on a moving deck; or
3) as an implementation to the SPN-10 (or SPN-42) system in the automatic landing mode in order to increase the probability of successful landing.

It is anticipated that if this system is successful, it will increase the safety of the landing operation and will also extend the range of sea conditions in which carrier operations will be possible. A system such as this one has a greater possibility of success, and appears easier to implement, than other suggested means for controlling the ship motion environment such as addition of antipitching fins [4], [5], which only have limited motion reduction capabilities and require fitting the ship with large appendages, additional powering units, etc. Thus the practicable implementation of the present system is another factor in its favor as a means for mitigating the influence of the sea environment on the landing operation.

As a result of the success exhibited in this first (analytical and model test) program, with proper accounting for extraneous influences such as possible bow waves propagated forward, the effect of oblique seas, etc. (which have been demonstrated to be only minor influences), it was then considered appropriate to extend this initial program into an actual full scale development whose performance could be checked during operations at sea. An outline of the procedures used for development and test of such a system, as well as a discussion of the results obtained, is presented in the present report.

This work was carried out at Oceanics, Inc. under the sponsorship of Air Programs Branch, Office of Naval Research, Department of the Navy, under Contract number Nonr-4186(00).

GENERAL DESCRIPTION OF ELEMENTS COMPRISING SYSTEM

The concept considered in the development of the prediction system requires as an input the wave motion time history, as measured ahead of the bow of the ship as it moves through the local wave field. Thus the first element required will be some type of wave height sensor, with associated additional components to produce a wave measuring system for this purpose. The wave height information must then be operated upon with a computer in order to generate a continuous output display of the predicted motions. In order to evaluate the effectiveness of the prediction, the display of predicted motions must be compared with a similar type display of actual ship motions as derived from a ship motions recording system. As part of the computer system, which will be a high speed digital computer, it will be necessary to have A-D converters and D-A converters in order to operate on the incoming wave signals as well as to develop the display of time histories of the predicted motions. A general representation of the data acquisition and signal processing system is envisioned according to the diagram in Figure 1.

The final output of the wave height measuring system will be operated upon with an A-D converter and fed into a digital computer, where the required mathematical operations of the prediction technique are to be performed. The digital output will then be sent through a D-A converter, and the predicted ship motion outputs will then be obtained as a continuous time history that can be recorded on a chart recorder and/or tape recorder.

The result will be compared to the actual ship motions measured on board the ship, which are assumed to be supplied from various gyros, accelerometers, etc. that are located on the ship (or from a ship motions recorder package.)

A detailed discussion of the various elements described in the preceding will be presented in the following sections of this report in order to describe the actual equipment used, the reasons for selection of particular devices and/or systems, as well as the analytical methods used for preparation within the computer system. Similarly the results of the operation of the entire system at sea, under realistic full scale conditions, will also be presented in this report.

WAVE MEASURING SYSTEM

Since the input data for the prediction technique is the time history of the wave motion measured at the bow of the carrier, it is necessary to develop a specific system for the purpose of obtaining continuous time history wave height data. This must be done from the ship while it is in motion at sea, from a particular reference point that would be fixed relative to the ship. The necessary element for such a system is some type of wave height sensor that would be able to provide a direct measurement relative to its instantaneous position while moving with the carrier (i.e. heaving and pitching with the ship), and to also include another device or system that would correct the vertical motion of the sensor itself. Thus the actual wave height would be obtained from the sensor output with a correction for the vertical motions of the sensor itself.

Two different types of wave height sensors were available for use in the proposed system, viz, an acoustic sensor and a radar sensor, with the acoustic sensor being roll stabilized. This particular acoustic sensor is described in [6], and it also includes a vertical accelerometer within the same instrument package which could then be directly utilized for the intent of this program. The radar wave height sensor is described in [7], and there is no stabilization of the unit itself. In order to compare the performance of the two sensors, comparative tests at sea were carried out aboard a Coast Guard cutter in the Atlantic Ocean, and the results of these tests as well as comparison of the

measurement capabilities of each sensor with a static reference are given in [8]. The investigation in [8] mainly compared the sensor outputs per se and not the final wave height that would occur when correction of vertical motions was made for each sensor, thereby allowing direct comparison of the performance of the sensors.

The results of this comparison showed that the data from both sensors agreed very well with each other, and that roll stabilization of the sensor unit would not be required in any application where small roll motions would be experienced. The radar sensor had a particular advantage relative to the sonic sensor since it could function effectively at any height when mounted on a ship, while the sonic sensor was limited to altitudes of approximately 45 ft. from the mean sea level. Thus the radar sensor was selected as the device for use in the present system.

The wave height record would be determined from the sensor output, together with a correction for the motions of the sensor itself which is determined by operating on the output of a separate accelerometer mounted adjacent to the sensor. The vertical motion of the sensor is given by double integration of the accelerometer output, and special considerations have to be applied to this type of integration procedure in order to avoid introduction of errors. The wave height is then expressed as

$$\eta(t) = h_b - s \qquad (1)$$

where s is the sensor signal output (relative to the "zero" reference distance to the undisturbed free surface level) and h_b is the vertical displacement of the sensor relative to the

equilibrium position of the sensor when there are no waves and the ship has no vertical motions. The term h_b is defined by

$$h_b = \iint \ddot{h}_b \, dt \, dt \qquad (2)$$

where $\ddot{h}_b$ is the vertical acceleration at the sensor location (measured positive upward). The particular methods of double integration considered, as well as the technique selected for the evaluation of measured data, are described in a later section of the report that covers computational methods.

The radar sensor was to be mounted on a support that would project out ahead of the bow somewhat, at a height above the water surface that would insure safety of the unit. (relative to the expected wave height and ship motions anticipated) and also allow rapid placement and removal. Examination of available space led to selection of the anchor and mooring cable-handling space on the 02 level of the FORRESTAL class carriers for location of the wave measuring system components, with the use of the port or starboard "Bullnose" opening through which the sensor support mounting was to be placed. The accelerometer package was intended for mounting within the ship, on the deck just adjacent to (and above) the radar sensor installation. In the actual implementation of the system on the carrier, a simple vertical accelerometer is intended for use (Donmer model 4310, which was used in the tests described in [8]), and this unit will be gimbal mounted and viscously damped. All necessary power supplies for the radar sensor, accelerometer, etc. are also placed within the ship on the 02 level deck in the bow region.

SHIP MOTION RECORDING SYSTEM

In order to obtain some measure of the actual motions of the carrier at sea, some type of ship motion indicating and/or recording system was required. Investigation was made of various possible systems or components that would be used for this purpose, with the point of view of availability, simplicity, and minimum interference with systems necessary for ship operations. The first system considered was the use of presently installed devices on board ship that could be used for determination of the ship's pitch angle as a continuous function of time. Examination of available ships equipment via visits to U.S. Navy offices in Washington, D.C., as well as examination of pertinent reference literature, indicated the possible use of the Mark 19 Gyro-compass and the Mark 5 Multi-speed Repeater for this purpose. Both of these devices present the ship pitch angle output data in the form of synchro signals, which involves a modulating carrier signal. The system proposed for the prediction operation uses varying d.c. voltages for the wave motion input, the processing within the computer and the final output presentation. Thus ship pitch angle signals representing actual ship motions would also be required to be the same type of varying d.c. signal. In order to transform the data from these devices to represent the pitch angle magnitude, as well as an indication of either direction ("bow-up"or "bow-down" pitch orientation) a synchro to d.c. conversion unit is necessary. Since these elements are located at some distance away from the available space for data processing, the signals must be transmitted along electrical cables of significant length. Thus there is a requirement that the unit must also be buffered in order to drive the signals

along these cables with minimum noise and "cross-talk". In addition it would also be required to calibrate this conversion unit in the presence of the operating measuring system, which might interfere with present use of these indicators on board the carrier. In view of these conversion, conditioning, etc. requirements, use of either of these devices as a source for the ship pitch angle data was not recommended.

Another possible source of ship motion data for the proposed system was the use of outputs that were being obtained in the course of the operation of the SPN-10 landing system aboard aircraft carriers. This particular system was being developed by Bell Aerosystems in Buffalo, N.Y. for use on large attack carriers such as those of the FORRESTAL class. At the time of investigation and preparation of the prediction system (summer 1966) the SPN-10 system was in the process of being modified from an analog to a complete digital system. The particular system on board any carrier at the time when the proposed tests of the prediction system were to be carried out would not be known precisely due to the problems of availability of carriers, status of development of the digital system, etc., and hence it was necessary to obtain information on all available data for the different operating concepts of the SPN-10 system. The particular data obtained from the measuring systems associated with SPN-10 were the ship pitch angle and the vertical displacement of the "touchdown" point which was defined to be at a particular desired location on the deck. All of these elements are contained within a so-called data stabilization system, which provides the ship motion monitoring capabilities for SPN-10.

With the emphasis on the digital form of the SPN-10

system that was evolving at Bell, the requirements of a tie-in capability with the needs of the prediction system were considered. The signals obtained from D-A outputs in the SPN-10 system were single ended and were also designed for use with close proximity magnetic tape recorders. The necessity of transmitting these signals an appreciable distance along cables to a locale where data processing was being carried out would require special amplifiers and hence increase the equipment and engineering costs for such signal transmission. In addition, the ship heave motions must be derived from knowledge of the vertical displacement of the touch-down point, together with scaling and summation of this signal with the ship pitch angle. All of these operations introduce certain problems and requirements for special equipment selection, and these require additional design considerations.

The possibility of interference with the signals that are being used directly in the SPN-10 system, by virtue of "tapping" from their main line and transmitting them to another region with the use of additional electronic gear, was viewed as a detriment to the SPN-10 system development. This was especially true since that system had not been proven or exercised at that time, and was only under development itself. As a result, it appeared that reliance upon use of data from other systems with a different main purpose aboard the carrier would not be expeditious for the present program. Thus another possible source of obtaining measurements of ship motions would be necessary.

Another source of equipment for obtaining ship pitch angle and ship heave acceleration (or vertical displacement) aboard an aircraft carrier was previously existing Government-owned systems that are used in present research studies. Particular interest was

given to the use of instrumentation that is applied by the David Taylor Model Basin (now known as Naval Ship Research and Development Center, NSRDC) in ship motion measurements at sea, and discussions were held with that organization in order to determine the capabilities of their equipment. A stable platform system was considered to be the most appropriate type for the measurement of ship pitch angle and heave acceleration, and the Mark 4 Mod. 0 system that has been used by NSRDC for a period of approximately 10 years appeared to be suitable for accomplishing this task. This system has undergone many modifications that were demanded by revising application requirements, with the modifications designed and implemented by NSRDC personnel. As a result, the original descriptive literature by the original manufacturer was not capable of properly describing the equipment, and only the experience of the personnel involved was used as the basis for consideration of possible application of this equipment.

The operating limits of this system are $\pm 20°$ in pitch, with maximum operating errors of $\pm 9'$ for pitch angle. The system has to be installed within 30 ft. of the ship's CG, and the basic environment has to be "electrically quiet". The physical application restraints inherent in the design of the Mark 4 system apparently preclude installation at the bow, based on limits of the circuitry and the mechanical elements present in the system. The NSRDC system contains all of the necessary signal conditioning equipment to obtain accurate low level signals, and eliminates noise and other interferences that are present in a shipborne environment. The requirements for location of the stable platform near the ship CG led to placement of this system in Emergency Generator Room No. 2 on the 3d deck. This stable platform re-

quires a special weld-mount of a reference plane on the floor of that room. The equipment also requires a cable run tie-in input from the ship's stable element, of the order of 80 ft. in length, and in addition the equipment requires a wire from the ship's EM log to provide ship speed input. The output information obtained from the NSRDC Mark 4 Mod. 0 stable platform will be ship pitch angle and heave acceleration, which corresponds approximately to the vertical acceleration at the ship CG, which are the required signals for this program. The availability of this equipment, together with the assistance of NSRDC personnel who were familiar with the system as well as with problems associated with full scale measurements at sea, led to selection of this motion recording system for use in the planned prediction system installation.

COMPUTER SYSTEM AND COMPUTATIONAL REQUIREMENTS

The basic technique used for the prediction of ship motion is based upon the continuous evaluation of a convolution integral, where the kernel function within the integral operates upon the input wave elevation time history (see [3]). Considering the generality of pre-programming different kernel functions in the computer memory, the generality of applicability required, and the compatibility with other computer systems on board a modern aircraft carrier, the choice of a digital computer for carrying out the prediction operations was a natural consequence. The particular computer selected for this work was the PDP-8 manufactured by Digital Equipment Corp., which was available as Oceanics, Inc. proprietary equipment. This computer is especially suited for the type of work required in this project.

Various peripheral equipment necessary for on-line data processing, as an adjunct to the computer, was required in order to complete the entire computational portion of the prediction system. This additional equipment included analog to digital (A-D) converters, multiplexers, and digital to analog (D-A) converters that were purchased as part of the required hardware for this project. Since the wave motion input data is a continuous time history analog signal, the internal computer processing is digital, and the comparative output signal of ship motion must also be in analog form (i.e. a continuous time history) the application of this additional computer peripheral equipment is a necessary element.

Another data processing operation required in the performance of this work is double integration of acceleration signals to

obtain displacement information, in the form of continuous time histories. Since integration per se is an open loop computer operation, with attendant "drift" problems, double integration presents even greater problems. In view of the main use of the digital computer for the motion prediction operation, the required double integration procedures are intended to be carried out with an analog computer and associated filter circuits (the analog computer is an Electronic Associates Inc. TR-48 transistorized model with the necessary capacity for this task). The double integrations required are for the purposes of determining the vertical displacement of the wave height sensor, as indicated in Equations (1) and (2), which is necessary for obtaining the true wave height, and also for determining the actual ship heave motion (at the CG) for measurements of the heave acceleration via the ship motion recording system.

The mathematical operations required for carrying out the prediction of ship motion, such as pitch angle for example, are represented in general by

$$\theta(t) = \int_{-\infty}^{\infty} K_\theta(t-\tau)\eta(\tau)d\tau \qquad (3)$$

where $K_\theta(t)$ is a kernel function that represents the time domain characteristics of ship pitch motion response. The ordinary kernel function that is used to represent present time ship motion, by operating on the present and past values of the wave motion, is

defined by the Fourier transform

$$K_\theta(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} T_{\theta\eta}(\omega_e)e^{i\omega_e t}d\omega_e \qquad (4)$$

where ω_e is the frequency of encounter (in rad/sec.) and $T_{\theta\eta}(\omega_e)$ is the complex transfer function between ship pitch motion and the waves encountered at the reference point ahead of the bow. This function is defined by:

$$T_{\theta\eta}(\omega_e) = \left|\frac{\theta}{a}\right| e^{i\phi_\theta(\omega_e; x_1)} \qquad (5)$$

where $\left|\frac{\theta}{a}\right|$ is the absolute magnitude of pitch angle response to sinusoidal waves, per unit wave amplitude, as a function of the frequency of encounter ω_e, and $\phi_\theta(\omega_e; x_1)$ is the phase angle of the pitch motion relative to the waves measured at the point x, at the bow (also as a function of frequency of encounter). Similar representations can be given for heave motion also.

The work in [3] used theoretically derived ship motion response characteristics, which exhibited good agreement in regard to amplitude characteristcis with limited model test data, to obtain the required kernel functions. These kernels, for equivalent full scale forward speeds of 20 knots and 30 knots in head seas, were further modified by neglecting the small magnitudes defined for negative time arguments (thereby making them "physically realizable") and by applying truncation by means of neglecting part of the initial time history (see [3]). The application of the modified kernel functions with measurements of irregular sea wave height data (from model tests) as input resulted in good agreement with experimental data for duplication

of recorded motion as well as for prediction of time histories up to 6 seconds ahead, full scale. On the basis of these results, further development was necessary to obtain kernel functions for other speeds and headings in order to allow generality and applicability to a greater range of conditions that might be expected to be encountered in full scale operations.

The determination of the required kernel functions follow from operating on ship motion transfer functions that reflect frequency response characteristics of the ship. A theoretical mathematical model for ship motion was available [1] and had been used in the previous work on this project. In addition a large set of model test data was available as a result of investigations carrier out at NSRDC (data from the studies described in [9]). Since limited phase information was available from the limited tests associated with the investigation reported in [3], the NSRDC data was considered for use in determining more extensive phase data as well as providing additional amplitude response characteristics. Examination of the NSRDC data showed that all phase measurements of ship motion, for all the degrees of freedom of the ship that were measured (all 6 motions) were referred to pitch motion as the base reference. However the present project requires pitch and heave motion phases relative to the wave motion, which is the fundamental causative agent of the resulting motions, and is the usual type of phase angle reference. Further study of the NSRDC data produced information in pitch angle phase relative to the wave motion but it was unreliable and had large scatter, mainly due to the influence of the model ship surge motion relative to a wave probe that was fixed with respect to the towing carriage

(while the model was free to surge). As a result no experimental phase information was available for use here, and thus only the theoretical phase angle values could be applied in development of the kernel functions. Since relatively reliable phase angle values are indicated by ship motion theory for low frequencies (i.e. long waves), the only region of possible discrepancy would be a higher frequencies where ship motion amplitudes are small and where only a small influence on response characteristics would be experienced. In addition the phase angles obtained from theory and/or experiment are relative to the wave at the CG, and they have to be modified by a phase shift to the reference point at the bow (a distance of 540 ft. from the ship CG or origin of coordinates), which introduces a large phase angle magnitude that is known precisely and alters the net phase angle of the frequency response functions. Thus the theoretical phase angles are expected to be sufficiently valid.

The only use of the NSRDC data was then for obtaining amplitude response data that would be compared with theoretical computations in order to arrive at a final form of amplitude frequency response that could be used in the evaluation of the required kernel functions. The influence of heading and forward speed could then be ascertained to a better extent than by theory above, and a "composite" frequency response function would then be established that weights the effects indicated by both theory and experiment. Comparisons between the theoretical motion amplitude responses for heave and pitch and the experimental data showed generally good agreement for head seas and wave headings of 30° off the bow (regular wave responses), with some deviation indicated at headings of 60° off the bow. Since the frequency

response characteristics of waves 60° off the bow did not "collapse" well as a function of frequency of encounter with the responses as head seas and smaller bow quartering headings, as shown by the results in [1] and [3], such wave headings are considered to be too large for effective application of the prediction concept. Similarly, it is not expected that any wave components in a real seaway, at such a relative direc.ional spread from the predominant wave direction (along the prevailing wind, which the carrier will be aiming to head into), will have any significant effect on the carrier pitch motions.

Composite response functions for amplitude and phase of both heave and pitch motions were then established at an average function that would adequately represent effects at heading angle- up to 45° off the bow, with an expectation that only small differences would occur in the final kernel functions for such heading angle variations, as indicated by the results in [3]. The computations were carried out at different headings for forward speeds in the range of 10 kts. to 35 kts., at 5 kt. intervals and a typical set of response functions for FORRESTAL class carriers is given in Figures 2-5 for the 10 kt. speed case. The final composite curves for this condition, representing the average influence of heading, are given in Figures 6-9 (the motions are defined as heave, positive upward, and pitch, positive bow down, leading to the phase angles given in the figures). The kernel functions, relative to waves measured at the bow, for this particular forward speed condition (i.e. 10 kts.) are obtained from these composite curves and are given in Figures 10 and 11. Applying a truncation of the small values of the pitch kernel

function for the first 6 sec. (and possibly for up to 8 sec. for this case) by neglecting the values of the function for that initial time will produce the predictor function in accordance with the theory in [3]. Examining the heave kernel function it is seen that no truncation of early time values is possible without significantly altering the kernel function, and hence no accurate prediction would be expected for heave motion by this technique. However, since pitch motion is the most important motion determing the carrier deck vertical motion as well as orientation, the ability to predict pitch motion adequately is then of major importance for the aircraft carrier application. While the above illustrative results are for one particular forward speed, viz. 10 kts., similar results are obtained for the other speeds treated (15-35 kts.).

The kernel functions for ship motion prediction, in accordance with the procedures described in [3] and illustrated above, are only functions of forward speed. They have a time extent of about 40 sec., without considering any truncation operation, and are to be applied to carry out the required prediction computations with a sampling time of 1 sec. Thus approximately 35 numerical values are required for each kernel function for storage in the computer memory, at each forward speed. Interpolation operations can be used for various intermediate speeds between those cases already computed.

According to the definition given in Equation (3), which is then modified by operations of physical realizability and truncation as shown in [3], the actual machine operation for

prediction ahead by T sec. is represented by,

$$\theta(t+T) = \int_{t-\tau_e}^{t} K_\theta(t+T-\tau)\eta(\tau)d\tau \qquad (6)$$

where τ_e is the time extent of the original kernel function (approximately 40 sec.). This operation produces the predicted pitch motion by means of the weighting of the past history of the encountered wave motion with the defined kernel function. Since these operations are only simple multiplication and summing, the total time of execution if measured in microseconds, including the time requirements for A-D and D-A conversions within the computer system. Thus the computations and the prediction operation are carried out sufficiently fast with the use of the PDP-8 digital computer and associated peripheral equipment to provide the necessary information for real-time applications.

The only other main computational operation required for this system is that of double integration of the bow accelerometer signal in order to obtain the true wave height. (See Equations (1) and (2)). Various circuits can be used for this purpose, with an initial low pass filter followed by a high pass filter that serves as a low frequency washout, which is then in turn followed by an approximate double integration operation. The purpose of these two initial filters is to eliminate any unnecessary noise in the system as well as the effect of any long term drift in the acceleration signal. However, an initial turn-on transient is expected when using such a system, which will take quite some time to decay and may give a false signal as a final output. In the presently conceived system

the necessity for a low pass filter is reduced by the absence of any significant noise in the bow accelerometer output signal, as indicated during the trials reported in [8]. However in order to effectively eliminate all extraneous noise sources (such as during catapult launching of aircraft) and also to eliminate any long term drift or d.c. offset that is present in the accelerometer signal, it is initially passed through a commercial filter (Krohn-Hite model No. 335) in sufficiently wide band-pass mode that eliminates such effects. The double integration operation is represented approximately by the transfer function

$$\frac{h_b}{\ddot{h}_b} \approx \frac{1}{s^2+2\zeta\omega_o s+\omega_o{}^2} \qquad (7)$$

where the values selected are $\zeta = 0.5$ and $\omega_o = 0.08$ rad./sec., which represents a resonant circuit of very low frequency lying outside the band of expected ship motion. The operation represented in Equation (7) is easily mechanized on the analog computer for this purpose.

Another mathematical operation considered in [3], but not implemented there, was a prediction of the wave motion [illegible] that could be used to increase the total prediction time. The modern development of filtering and prediction, using methods originally developed by Kalman[10], would be appropriate for the present method as long as a proper mathematical model representing the "dynamics" of the process producing the wave motion could be established. Considering various possible forms of the wave spectra that are experienced at sea, a possible simple

model would be represented as the result of a second order oscillator circuit operating on a white noise input, with a transfer function of the form

$$\frac{\eta}{n} = \frac{s}{s^2+2\zeta\omega_n s+\omega_n^2} \tag{8}$$

with ω_n corresponding to the central frequency, i.e. the frequency for the largest value of spectral density, and ζ a measure of the bandwidth properties, and where n is the white noise input.

With the assumption that no measurement noise is present, i.e. perfect observation, and considering the basic dynamics to be that corresponding to a simple (constant coefficient) second order system, the predicted state vector (T sec. ahead) is represented by

$$\hat{x}(t+T) = \phi(T)x(t) \tag{9}$$

where

$$x = \begin{vmatrix} \eta(t) \\ \dot{\eta}(t) \end{vmatrix} \tag{10}$$

and $\phi(T)$ is the state transition matrix for the second order system (see [11]), where the state transition matrix represents the basic impulse response characteristics of the dynamic system. In the second order system represented by Equation (8), the

transition matrix is

$$\Phi(T)=e^{-\zeta\omega_n T}\begin{bmatrix} \cos(\omega_n\sqrt{1-\zeta^2})T+\frac{\zeta}{\sqrt{1-\zeta^2}}\sin(\omega_n\sqrt{1-\zeta^2})T & \frac{\sin(\omega_n\sqrt{1-\zeta^2})T}{\omega_n\sqrt{1-\zeta^2}} \\ \frac{\omega_n}{\sqrt{1-\zeta^2}}\sin(\omega_n\sqrt{1-\zeta^2})T & \cos(\omega_n\sqrt{1-\zeta^2})T-\frac{\zeta}{\sqrt{1-\zeta^2}}\sin(\omega_n\sqrt{1-\zeta^2})T \end{bmatrix} \tag{11}$$

so that the predicted wave height T sec. ahead is given by

$$\hat{\eta}(t+T)= e^{-\zeta\omega_n T}\left[\cos(\omega_n\sqrt{1-\zeta^2})T+\frac{\zeta}{\sqrt{1-\zeta^2}}\sin(\omega_n\sqrt{1-\zeta^2})T\right]\eta(t)$$

$$+e^{-\zeta\omega_n T}\,\frac{\sin(\omega_n\sqrt{1-\zeta^2})T}{\omega_n\sqrt{1-\zeta^2}}\,\dot{\eta}(t) \tag{12}$$

Thus it is necessary to have a record of $\dot{\eta}(t)$ as well as $\eta(t)$, but simple differentiation can be applied with sufficient accuracy to provide that record, and the predicted value of wave height is then given in the form of Equation (12). The effectiveness of this procedure is dependent upon the general form of wave spectra actually encountered at sea (i.e. whether a second order representation is sufficiently valid), and also upon the parameter values if the proposed model of the wave spectra is adequate. This will be determined in the course of operations on real data obtained at sea in this program.

SHIPBOARD INSTALLATION AND TEST CONDITIONS

The various subsystems described in the foregoing sections were planned for installation on an aircraft carrier of the FORRESTAL class, with the wave measuring system located in the bow region and the ship motion recording system in Emergency Generator Room No. 2. The computer system was also located in the same Emergency Generator Room No. 2, thereby necessitating a cable run of approximately 500 ft. from the measurements of waves at the bow. The installation of all elements was to proceed with the assistance of Naval Shipyard personnel, which would be supplied by the Norfolk Naval Shipyard. The ship that was available for these tests was the USS INDEPENDENCE (CVA-62) which was available at Norfolk in the winter period of 1967-1968.

The cable from the bow to the data processing area was a single coaxial cable of 1/4 in. diameter denoted as TTRS-4, a type of wire that has been successfully used for similar signal transmission on other full scale test operations. All assistance by the Fleet and various Naval organizations was authorized under CNO project D/S 430, "Carrier Deck Motion Prediction". The installation was carried out by shipyard personnel with the assistance of personnel from NSRDC and Oceanics, and tests were planned in association with ship sailings for other specific operational purposes. The tests of the ship motion prediction system were to be carried out during open sea operations on the carrier on a "not to interfere" basis with normal ship operations, which were to be mainly shakedown cruises after shipyard overhaul as well as carrier qualification tests for various Naval aircraft squadrons.

A number of sea trials were carried out under this project starting with the initial tests in March 1968, which were carried out in the region south of Norfolk, Virginia and extending down toward the northern region of Florida. A subsequent test was aimed at obtaining data during a long period journey at sea, and was planned in association with the voyage of the INDEPENDENCE back to Norfolk after duty with the 6th Fleet in the Mediterranean. This involved shipment of all the necessary equipment to the island of Majorca, where the ship was in port for a one week period, in January 1969 so that installation would be made there. All cable installations had to be redone due to removal of the initial shipyard installation, and this was carried out with the aid of ship personnel. The return voyage to Norfolk was expected to take 8-9 days, thereby offering opportunities for open sea conditions in the Atlantic Ocean. Further tests were carried out on board the INDEPENDENCE during a voyage from Norfolk to Guantanamo, Cuba at the end of April 1969 as well as participation during voyages of that ship from Norfolk, Va. to Jacksonville, Fla., and return, in December 1969. During all of these voyages one or more representatives of Oceanics, Inc. were present, and in addition a representative of NSRDC as well (except for the December 1969 trips). The results obtained during these various test periods are discussed in the following section.

DISCUSSION AND ANALYSIS OF TEST RESULTS

The first tests carried out in March 1968 were significant in that large sea conditions were encountered during a large portion of the time at sea. The wave heights present were often up to 18-20 ft. in magnitude, and were sufficient to excite meaningful ship motion (significant pitch angles up to 1.2°, double amplitude). However, the tests were inconclusive in regard to determining the effectiveness of the prediction system for a number of reasons, although all components comprising the system functioned satisfactorily throughout the test period. Very high winds, of the order of 30-35 kts., were present during the tests, and in order to accommodate the requirements of the aircraft landing operations (which was the main purpose of the ship cruise), very little headway was maintained by the ship, i.e. the forward speeds were about 2-3 kts. maximum during the times when sufficient wave action was present. Since the kernel functions for prediction were prepared for use with the computer system for forward speeds of the order of 10 kts. and above, no possibilities existed for on-line application of the prediction technique for the low speed range experienced.

In addition, the validity of the properties of any kernel functions for low speeds in regard to the required small variation with heading, as indicated by the results in [3] and the computations illustrated previously herein, was not known at that time. Furthermore, there are problems associated with possible wave generation due to the ship's own motions in response to on-coming waves that might interfere with proper measurement of waves at the bow at low speeds. Since the demonstration of capability in [3]

was based on sufficiently high speeds where that phenomenon was not experienced, the extent of influence of such possible interference with the wave patterns is not known. An investigation of the significance of these effects and the capability of prediction under such low speed conditions was deferred on the assumption that further data would be obtained under more favorable conditions for evaluation of the proposed prediction technique.

In order to obtain more appropriate environmental conditions, where ship forward speeds would be in the range appropriate to the expected region of validity of the prediction technique as well as where the ship would experience sufficiently large wave disturbances, the arrangements were made to accompany the USS INDEPENDENCE on its return to the U.S. from duty in the Mediterranean Sea. The return voyage across the Atlantic Ocean in January 1969 was expected to provide the idealized test conditions that were desired. All outfitting and installation of the different system elements was completed while the ship was in port at Majorca and the return voyage through the Atlantic Ocean followed the departure from Majorca. After passing the Azores the seas became very rough and large ship motions occurred. The ocean environment was such that a combination of large waves and resultant large ship pitch motions occurred so that the waves smashed the radar sensor and made it ineffective within a few minutes after encountering the wave disturbance. This event demonstrated that placement of the radar sensor at a height of 43 ft. above the mean free surface level (in the Bullnose opening at the 02 level) would not insure safety of the unit and also would not allow proper data acquisition in very high seas.

The radar sensor was repaired within less than two days after the encounter with this large storm and replaced in its original position in order to obtain data under somewhat less severe conditions that might still be useful for evaluating the prediction technique, e.g. wave motions similar to those experienced in the March 1968 tests. Unfortunately, the Atlantic Ocean did not experience any other significant wave disturbances along the southerly route followed by the ship during the time of its voyage from the Azores back to Norfolk, Va. Thus no significant sea disturbances were available for determination of the system performance during that particular voyage.

In an effort to alleviate the problems associated with damage to the radar wave sensor when it was located in the anchor handling space at the 02 level, a redesign of the mounting and its location was made after the ship was in port. This modification, carried out with the assistance of the ship's crew, resulted in a simple support that allowed the sensor to be placed in a higher position. The radar could then project a signal directly down to the sea surface, as required, while it was mounted at the highest possible point on the ship without interfering with any other ship operations, viz. at the level of the secondary conning position just below the flight deck at the bow. The sensor was then located at a height of 57 ft. above the mean free surface level and would not be expected to experience any interference during the time when it was operating under test conditions. Any disturbance that would cause impact with the sensor at that height would not be a condition under which testing would be carried out, nor would it be a functionally operational condition for an actual installation for use during

ship operations in view of the severity of the motions that would limit aircraft landing operations on the carrier.

The tests in April 1969 during the trip to Guantanamo Bay, Cuba and also the tests during December 1969 where the INDEPENDENCE was operating between Norfolk and Jacksonville were carried out in an attempt to experience some wave and ship motions that could provide useful data for evaluation purposes. The particular test times and geographical regions for the ship operation were dictated by Fleet requirements, carrier qualification trials, etc. and the decision regarding possible testing was thus based upon the availability of the ship going to sea. The experience on these particular test trips (April, December 1969) was a lack of any appreciable wave motion, and subsequent ship motions, so that no useful data was obtained during those tests for evaluation of the present prediction method.

Since the only significant data obtained in the various full scale tests at sea was that from the March 1968 sailing, an examination was made of the possible application of that data for evaluation of the various operations associated with the prediction technique. This was carried out in order to determine possible limits of applicability of the concept, while evaluating the properties of the ship responses (in the frequency domain) and the resulting kernel functions, as well as indicating the nature of the results obtained with realistic full scale data.

In order to obtain the kernel functions for the speed of 2.5 kts. and other speeds of interest below 10 kts., computations were made of the ship motion responses in heave and pitch at speeds of 0, 2.4, 5 and 7 kts., at headings corresponding to head seas

and other headings of 30°, 45°, and 60° away from pure head seas. The pitch and heave amplitude responses were compared with experimental data for speeds of 0 and 5 kts., and good agreement was found between theory and experiment within the limits discussed previously in regard to heading variation (poorer agreement at 60° deviation from head seas, but good agreement for the other experimental cases up to 30° off the bow). Following this comparison, the calculated responses for the forward speed of 2.5 kts. were used to obtain the necessary kernel functions, with the resulting pitch kernel having similar properties as for the other speeds considered previously, and similarly for the heave kernel function. The large magnitude of the heave kernel for small initial values of time also appeared to preclude any prediction capability for that mode of motion, while the pitch case is still capable of predicting up to about 7.5 sec, by virtue of the truncation procedures inherent in this technique.

Some of the test data obtained in the March 1968 cruise was then analyzed and processed further in order to determine the effectiveness of the proposed technique. The first operation was that of double integration of the bow accelerometer signal and combining it with that of the radar wave sensor to produce a total wave record. Typical data records obtained by this procedure are illustrated in Figure 12, where it can be seen that the radar wave sensor output has more high frequency content that that of the bow accelerometer including some small irregular noise that is not expected to be significant. The bow accelerometer record seems to be more "periodic" in nature, indicating a narrow-band property, and it is very similar in form to the pitch motion record. Thus

the ship effectively acts as a filter on the wave input, and the predominant influence of pitch on the vertical motion of the extreme ends of the ship is indicated by this result (such characteristics were found for almost all of the runs obtained in these tests).

The kernel function for pitch for the forward speed of 2.5 kts. was applied to the resulting total wave motion record obtained by combining the wave sensor output with that of the doubly integrated bow accelerometer signal. The results obtained by use of the entire kernel function itself in its complete definition, i.e. without any truncation, were aimed at just obtaining a reproduction of the ship pitch motion. This could be compared with the actual motions in order to determine if the kernel function, when operating on the wave record input, would duplicate the motions actually experienced at sea. Unfortunately, no agreement whatsoever was obtained in regard to the pitch motion, which is at variance with results obtained in [3] as well as in many other model test investigations. There are many possible causes for this inability to obtain agreement, and they include the possibility of the influence of the wave component directions, poor representation of response properties, improper wave measurement, and interference by ship-generated waves.

The question of wave direction influence does not appear to be significant since the wave system at sea did not appear to have very confused patterns (in regard to direction). The data was obtained with the ship heading into the wind (or at least with only a small deviation in order to obtain wind along the canted deck at an angle of approximately 10° relative to the fore-and-aft centerline), and all model test data has indicated only a small influence of wave direction under these circumstances. A possibility also exists that

the determination of the wave record by the instrumentation aboard ship was not correct, but in each case the separate components were individually checked and found to function effectively. The double integration operation produced an output signal that had the expected characteristics in view of the narrow-bandedness of the bow accelerometer signal, and the summing operation produced a realistic appearance of the resulting wave record. Since each of the separate components and the operations on them were performed adequately, there is no reason to expect any improper functioning of the wave measuring system.

Another possible source of error would be a poor kernel function representation, which would possibly occur due to errors in the determination of the "composite" amplitude curve and/or phase curve representing frequency response. In an effort to check the sensitivity of the kernel function, some changes were made in the form of the amplitude and phase of pitch response in the higher frequency region, i.e. for values of $\omega_e \geq 0.55$ rad./sec. When the new values of frequency response were applied in the determination of the pitch kernel function only small differences were obtained, which were in regions for larger values of time (i.e. in the argument of the kernel function itself) as well as producing only small local changes in maximum amplitude of the "oscillatory" portion of the kernel function. No significant change in the computations determining pitch would occur on the basis of such a modification to the kernel function and hence the effect of any high frequency deviation in pitch responses is not significant. Since good agreement is always obtained for the lower frequencies in the range of interest (i.e. longer waves), the kernel function appropriate to this case is

is expected to be a valid representation of ship response properties in the time domain.

The remaining possible source of error in this case is due to the influence of ship-generated waves that could interfere with the oncoming wave system at the bow where the measurements are being made. Thus the observed wave records obtained from these measurements would not reflect the direct wave system that distrubs and causes the ship motions, which is the required information for this technique, but would include extraneous effects that change the wave time history that is used as the input in this program. Previous hydrodynamic analyses (e.g. [12]) of wave motions created by free surface disturbances that both oscillate and translate simultaneously have shown that time-varying waves are propagated forward, i.e. ahead of the moving disturbance, under conditions that correspond to the relationship

$$\frac{\omega_e V}{g} < \frac{1}{4} \tag{13}$$

where ω_e, the encounter frequency here, is the oscillation frequency, V is the forward speed, and g the acceleration due to gravity. For the present case of motion in an irregular sea that contains a range of frequencies, within which the ship responds in its motions as an effective filter, the lower frequency value expected for any appreciable motion that could cause wave generation sufficient to disturb the wave measurements at the bow would be about $\omega_e \sim 0.5$ rad./sec. On this basis a forward speed of the order of 10 kts. or higher is the critical speed that is required to eliminate any interference waves, and hence for proper testing of the present concept that uses measured

waves as the input. It may still be possible to obtain the necessary measurement of proper wave input data at lower speeds, dependent on the particular sea state conditions present, for testing the prediction technique but that must be determined by more detailed considerations in each individual case (not as a general principle). The particular test conditions at the low forward speeds of 2-3 kts. encountered during the March 1968 tests were certainly instances where significant wave interference could be expected, thereby invalidating the data obtained there as a proper test and/or evaluation of the prediction technique in this program.

Although the data obtained at the low forward speeds could not be used for evaluating the capabilities of pitch motion prediction, other uses of this data were possible since it represents useful full-scale measurements. One of the other computational efforts associated with the proposed prediction technique is the prospect of predicting the wave motion for some small increment of time ahead from measurements of the wave motion time history up to the present time instant. This procedure has been described previously in this report, with the basic equations given by Equations (9)-(12).

Some of the data obtained in these tests was separately processed at NSRDC and power spectra were obtained for the separate measurements, as well as the results of integration operations on some of them. The power spectra allowed the determination of the central frequency of the different components entering into the total wave record at the bow and also allowed an estimate of the bandwidth as well. On this basis the parameters entering into Equation (12) were found to be ω_n=0.6 rad./sec. and ζ=0.2. Using these values together with the total signal representing the wave height time

history, $\eta(t)$, the estimates of predicted wave time history for prediction times of T=1 sec., 2 sec., and 3 sec. were determined. From the numerical values of the parameters it was seen that a prediction for 3 sec. ahead would not be practicable, and it remained to determine whether adequate prediction was possible for 2 sec. as a useful quantity for this work.

The results obtained by this procedure, after appropriate filtering to reduce any noise in the signals due to the differentiation operation on the $\eta(t)$ signal, are given in Figure 13. It appears that an adequate prediction up to 2 sec. ahead is possible for the waves that are observed as a result of measurement, by means of the technique given in Equations (9)-(12). Any possible effects of higher frequency noise fluctuations are expected to be filtered out in the course of the prediction technique for pitch motion applied with the truncated kernel operating on the predicted time history. The successful application of prediction with the advanced prediction time of the wave illustrated here would produce a sufficiently longer prediction time for use in aircraft carrier operations, and the effectiveness under more appropriate conditions than those experienced in the present full-scale tests should be determined by means of further tests at sea. In that case the determination of the parameter values of ω_n and ζ (for use in the Kalman predictor) from a time history record of the waves as measured on the ship can be accomplished by other procedures, with the determination of the wave spectrum central frequency ω_n being the most significant parameter required. The details involved in such processing of wave records is a task that can be considered as part of the later effort, and is not expected to present any difficulties at that time.

CONCLUSIONS AND RECOMMENDATIONS

The main result of this investigation has been the establishment of all of the necessary equipment required for the functioning of a ship motion prediction system, which can then be used for full scale evaluation purposes. All necessary hardware items have been evaluated and the most suitable for the purpose of the program have been obtained, checked, and applied for their specific purposes. The computational requirements have been satisfied by means of the different computer operations that have been applied by the various elements involved in the data processing system, with adequate performance obtained for the separate computations required for implementation of the proposed technique. Thus a complete system has been made available for use in obtaining full scale data and evaluating the capabilities of ship motion prediction by means of the technique described here, which was originally developed in [3].

While the environmental conditions experienced in the different tests reported herein have not been suitable for proper evaluation of the concept, for the reasons discussed within the report, the system can be utilized under more suitable conditions for evaluation purposes. It is only necessary to have the carrier proceed at sufficiently high speed in wave systems where significant motion that would affect the aircraft landing process would be experienced, and those conditions would provide an appropriate set of test conditions for evaluation of the prediction technique. The performance thus far, as well as the indication of capabilities of carrying out certain ancillary and associated operations of data processing, is sufficient to provide a basis for continuing this

program by means of further full scale testing. It is therefore recommended that further support be provided in order to achieve a proper evaluation of the feasibility of predicting carrier deck motion. The possibility of increased safety in aircraft landing operations aboard carriers with the use of the proposed prediction system is the basic consideration for continuing the full scale investigation of this concept.

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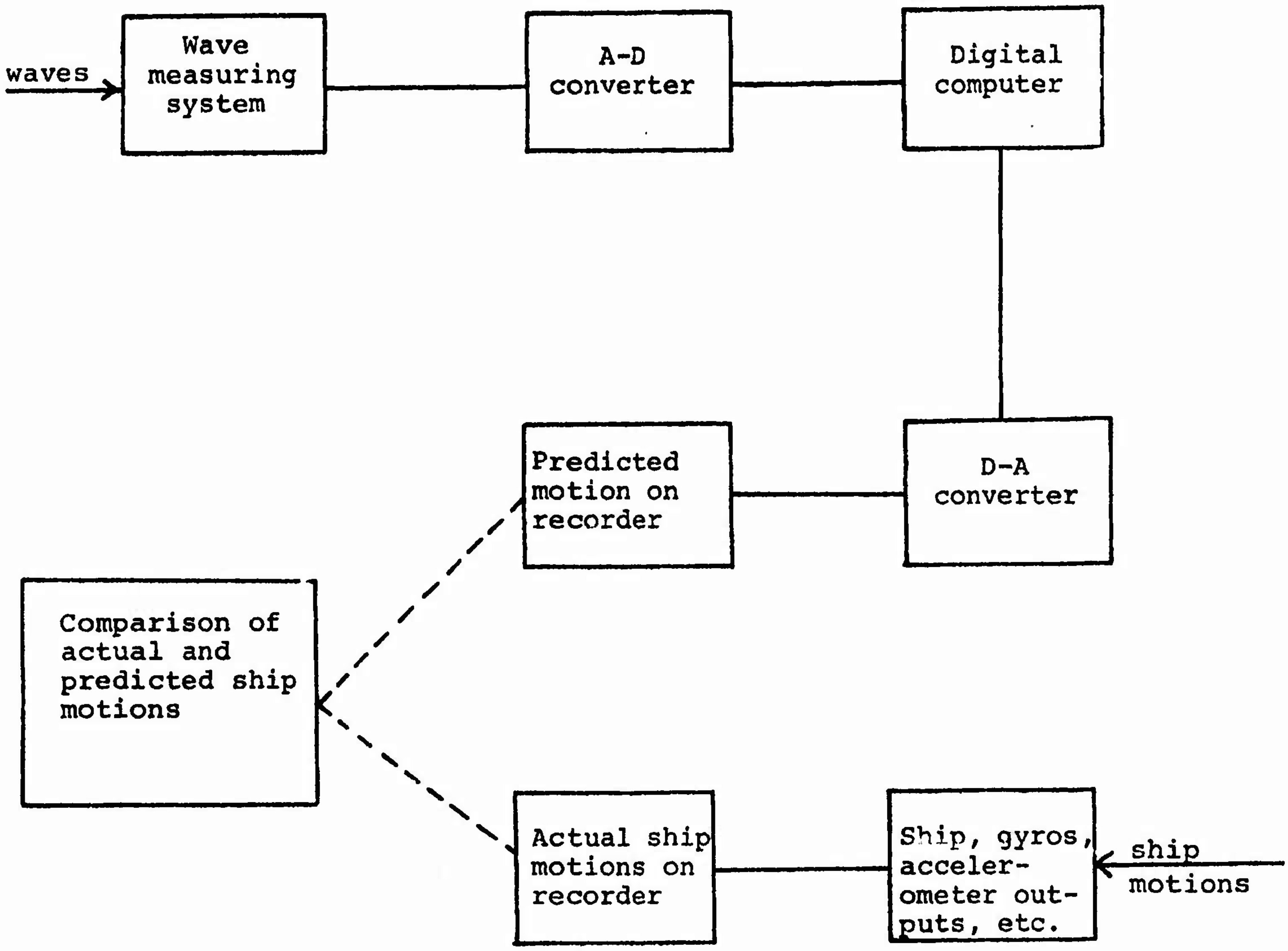

Fig. 1 Proposed signal processing and prediction system

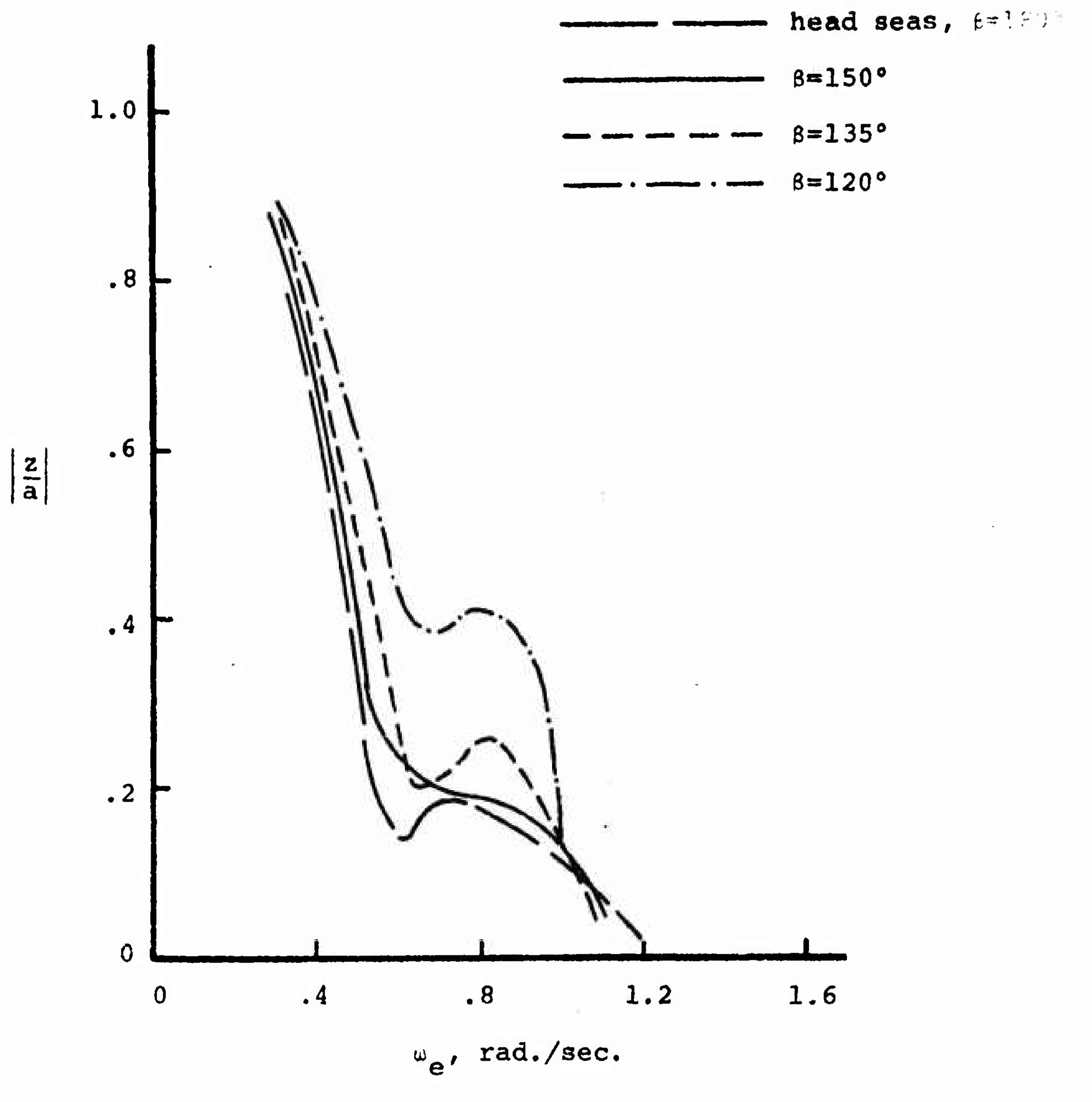

Fig. 2 Heave amplitude frequency response characteristics, V= 1[illegible] kts

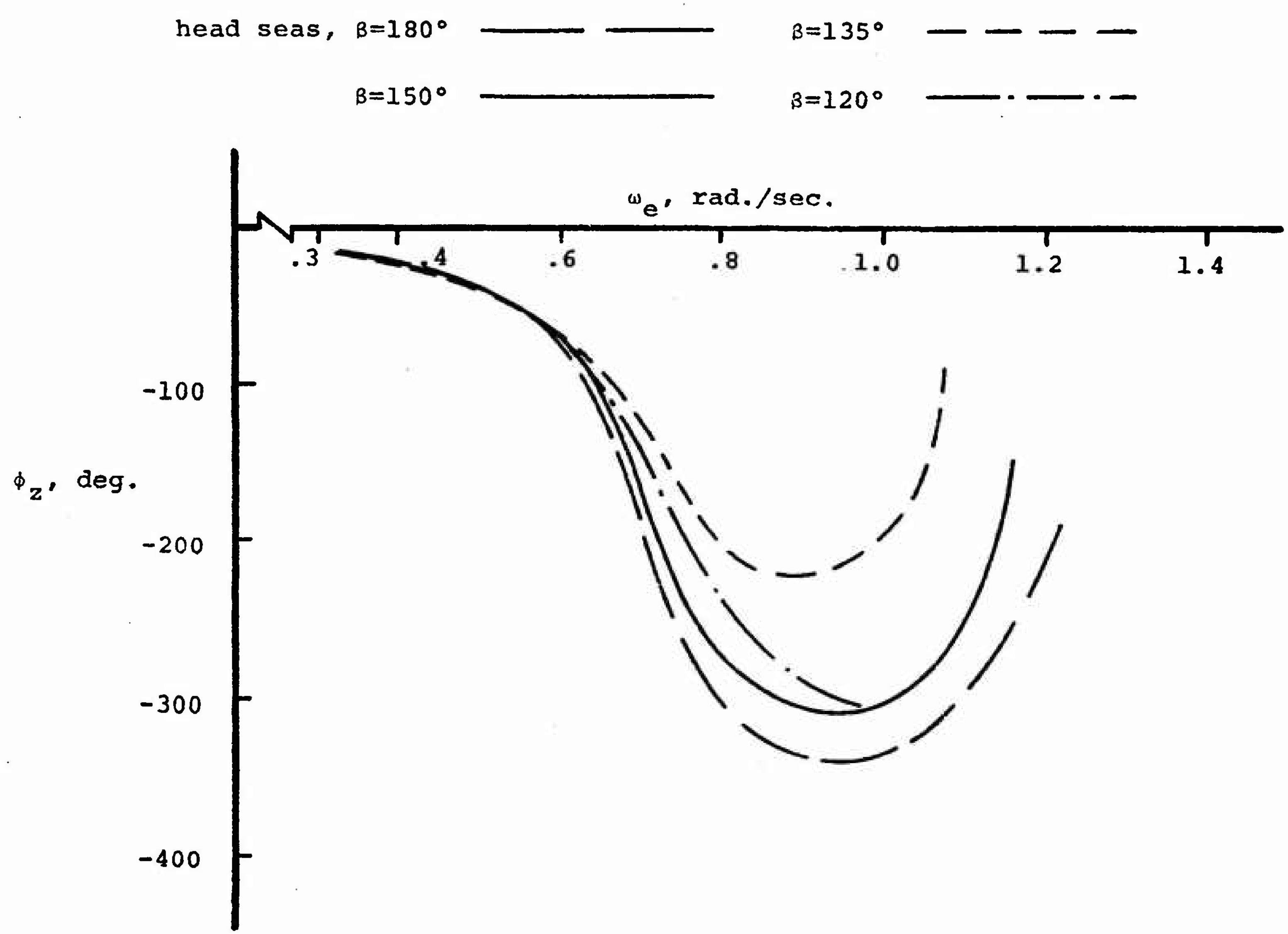

Fig. 3 Heave phase frequency response characteristics, V=10 kts.

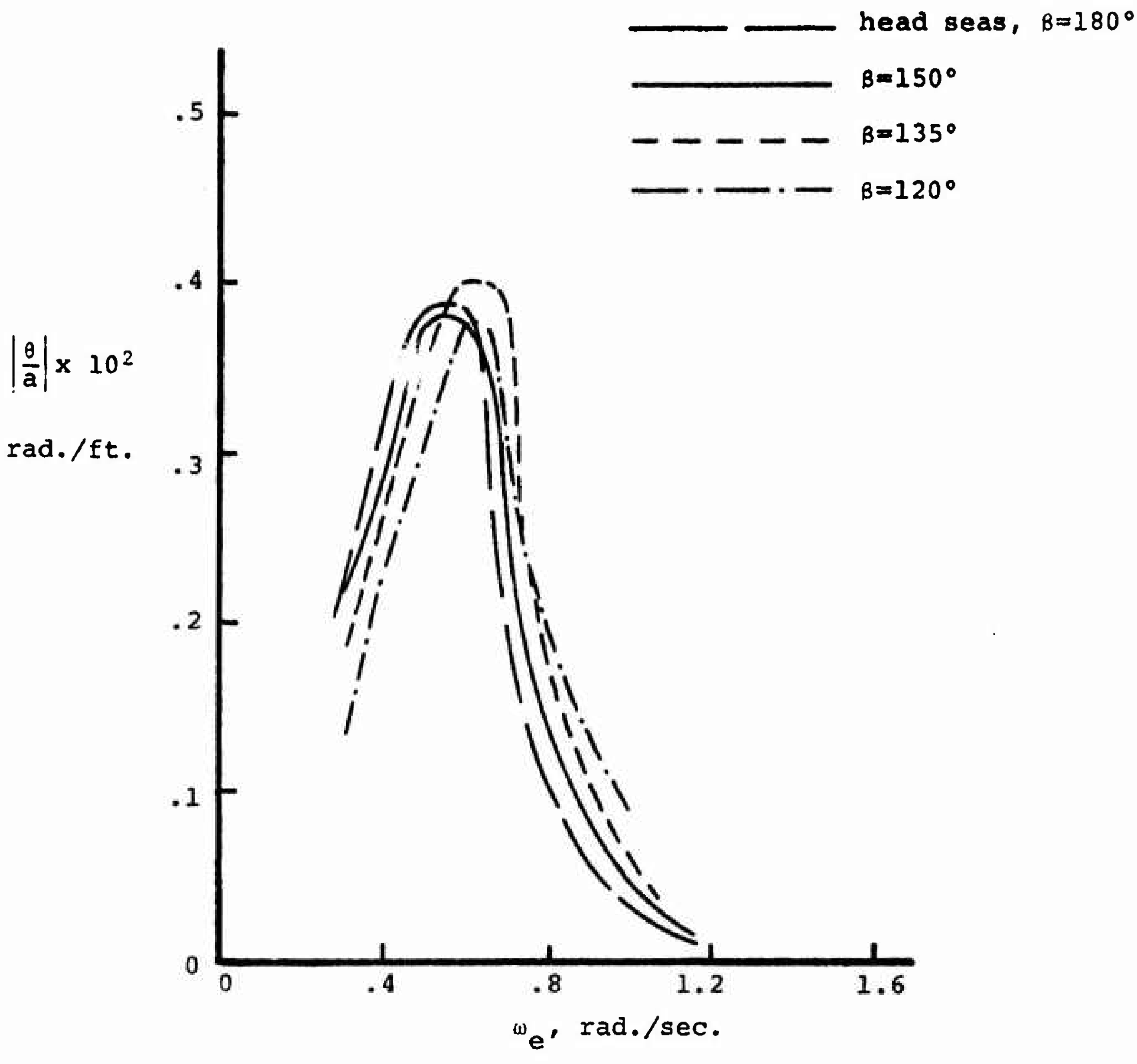

Fig. 4 Pitch amplitude frequency response characteristics, V=10 kts.

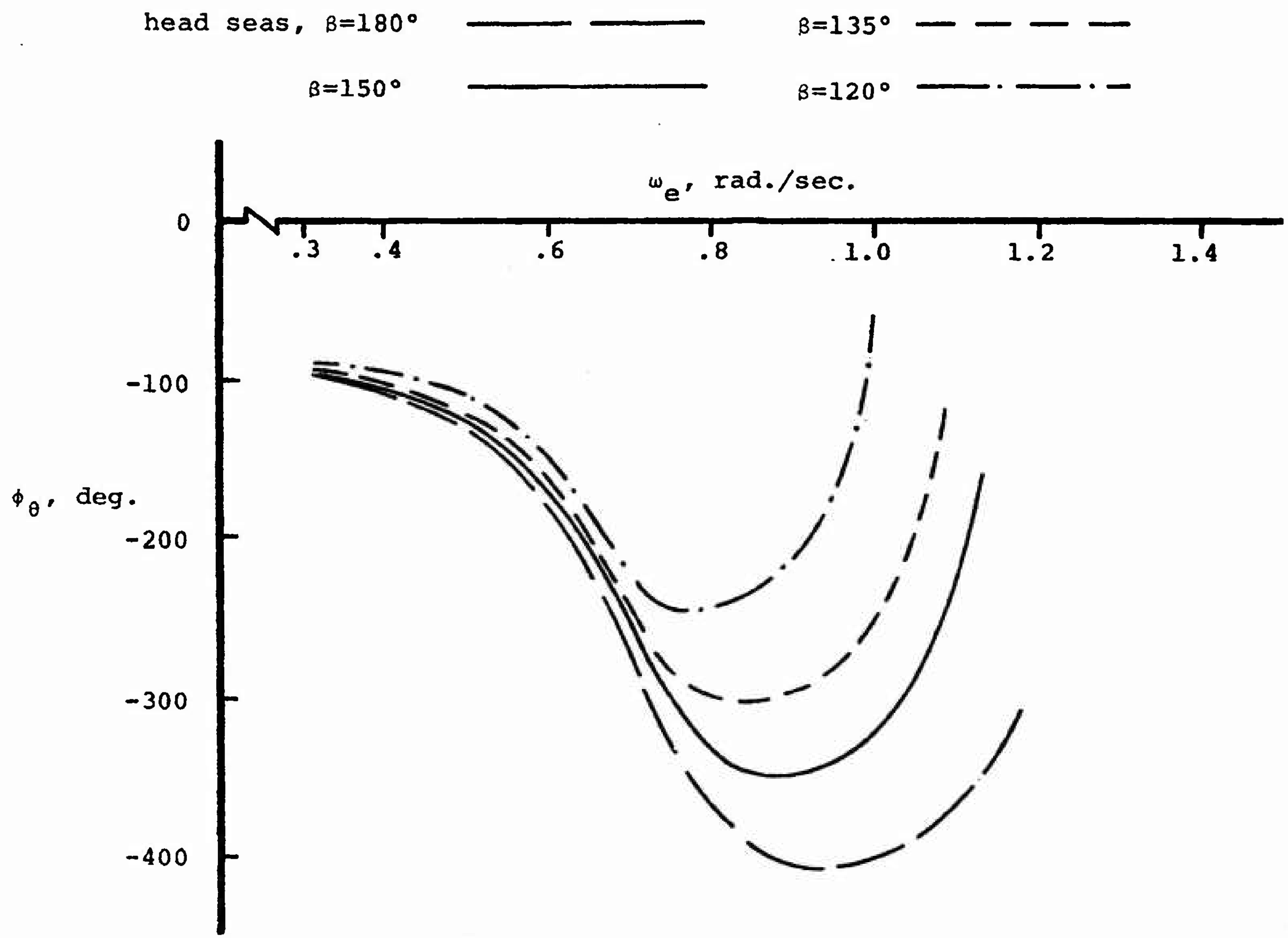

Fig. 5 Pitch phase frequency response characteristics , V=10 kts.

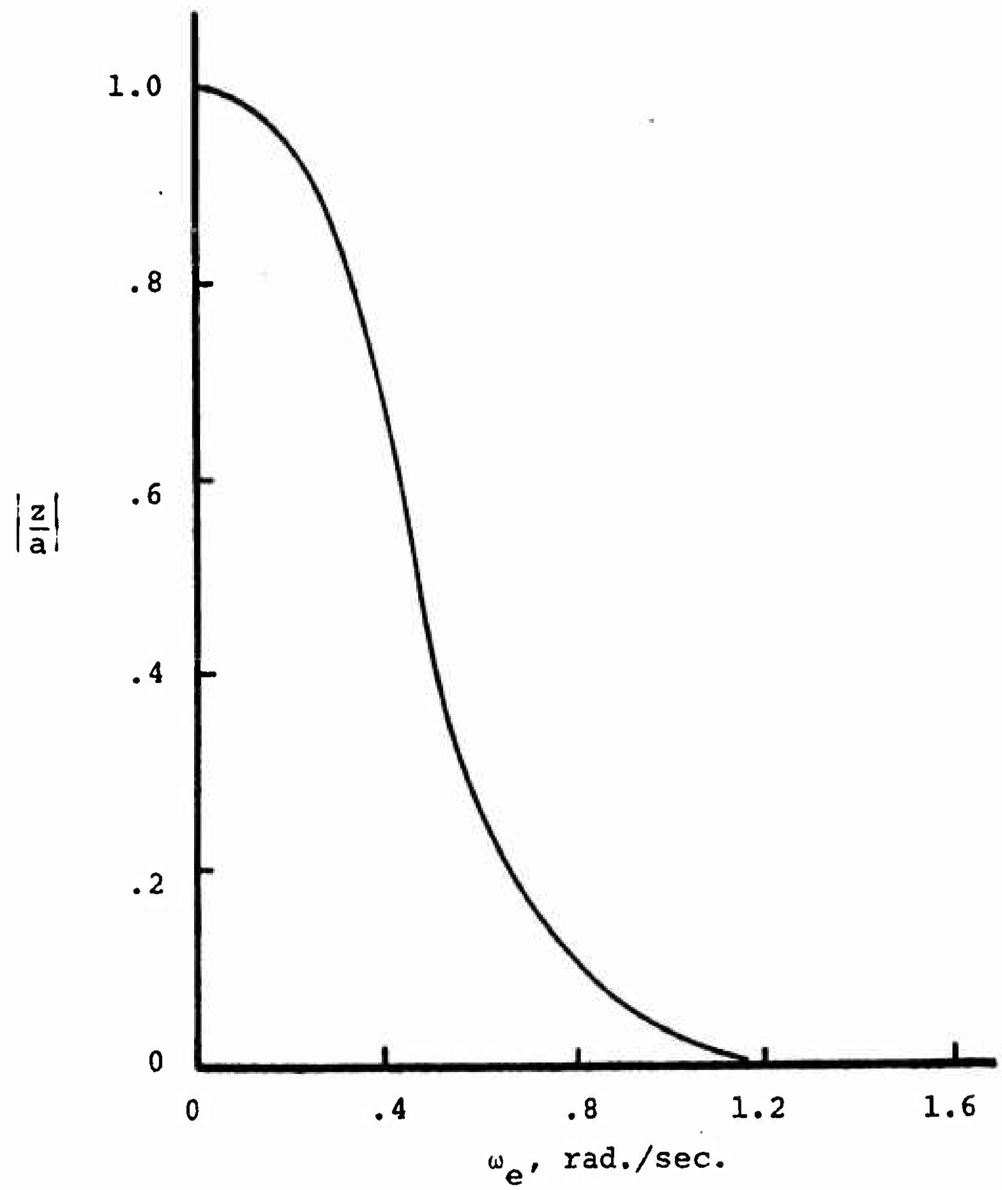

Fig. 6 Composite heave amplitude frequency response, V=10 kts.

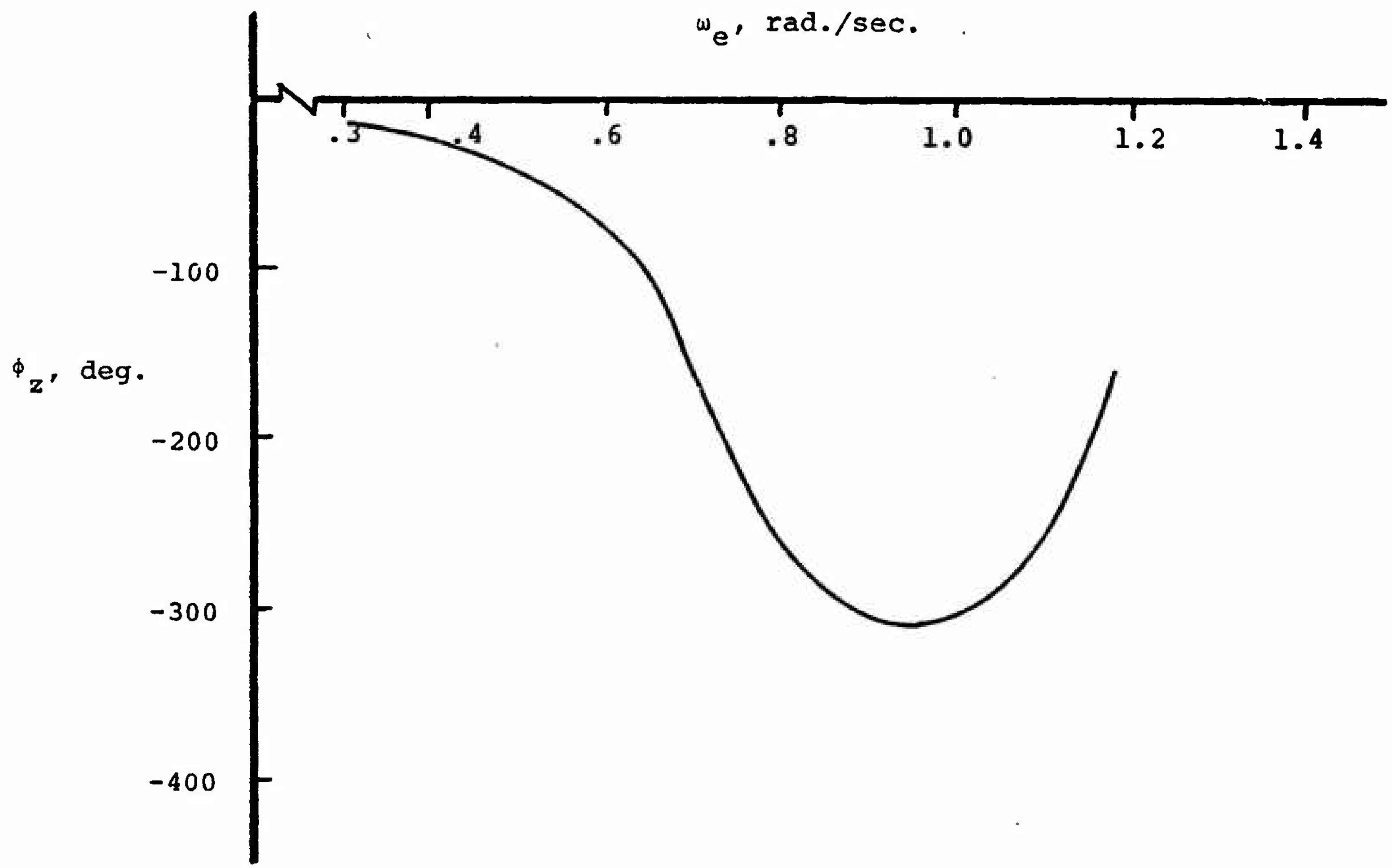

Fig. 7 Composite heave phase frequency response, V=10 kts.

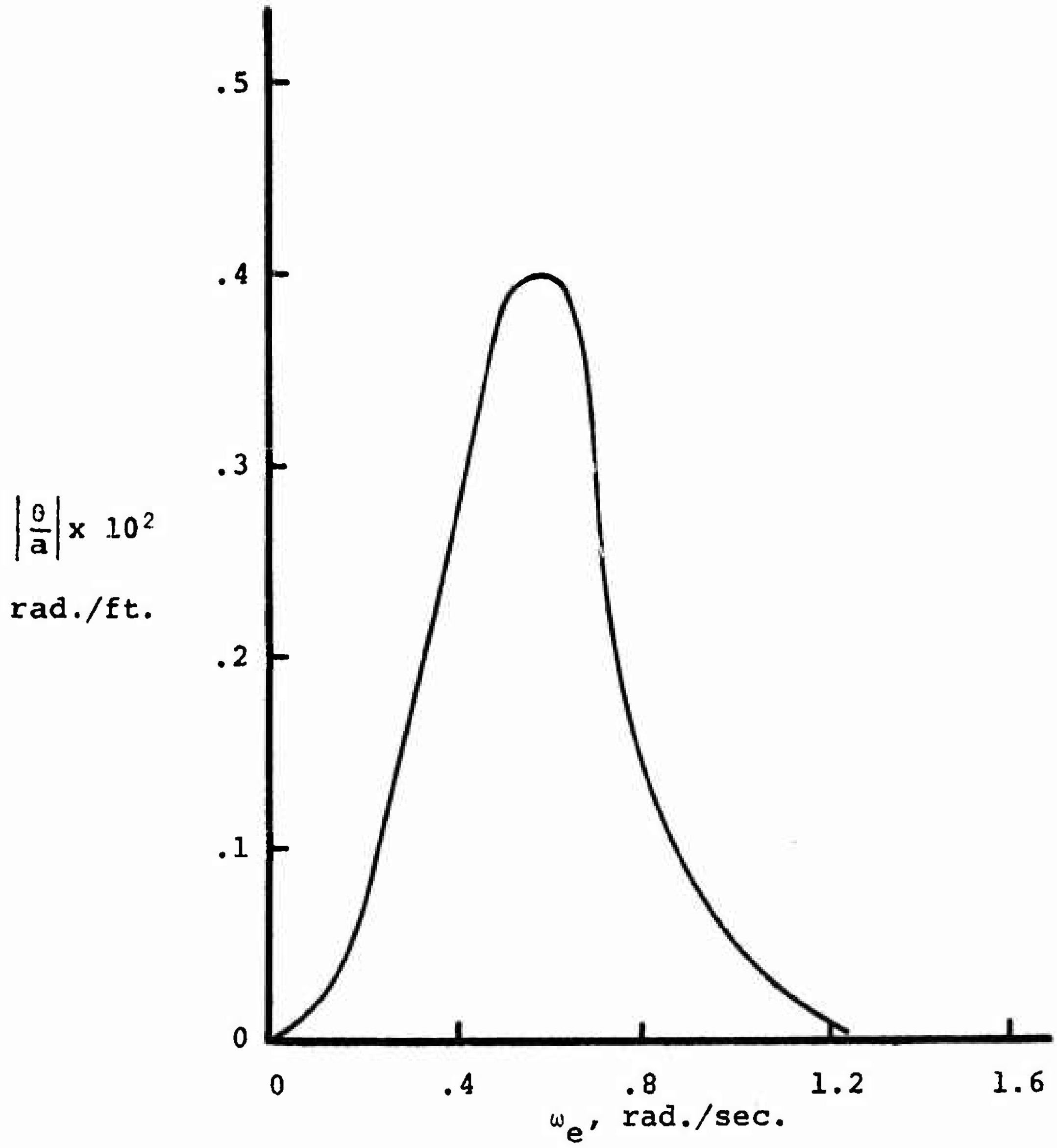

Fig. 8 Composite pitch amplitude frequency response, V=10 kts.

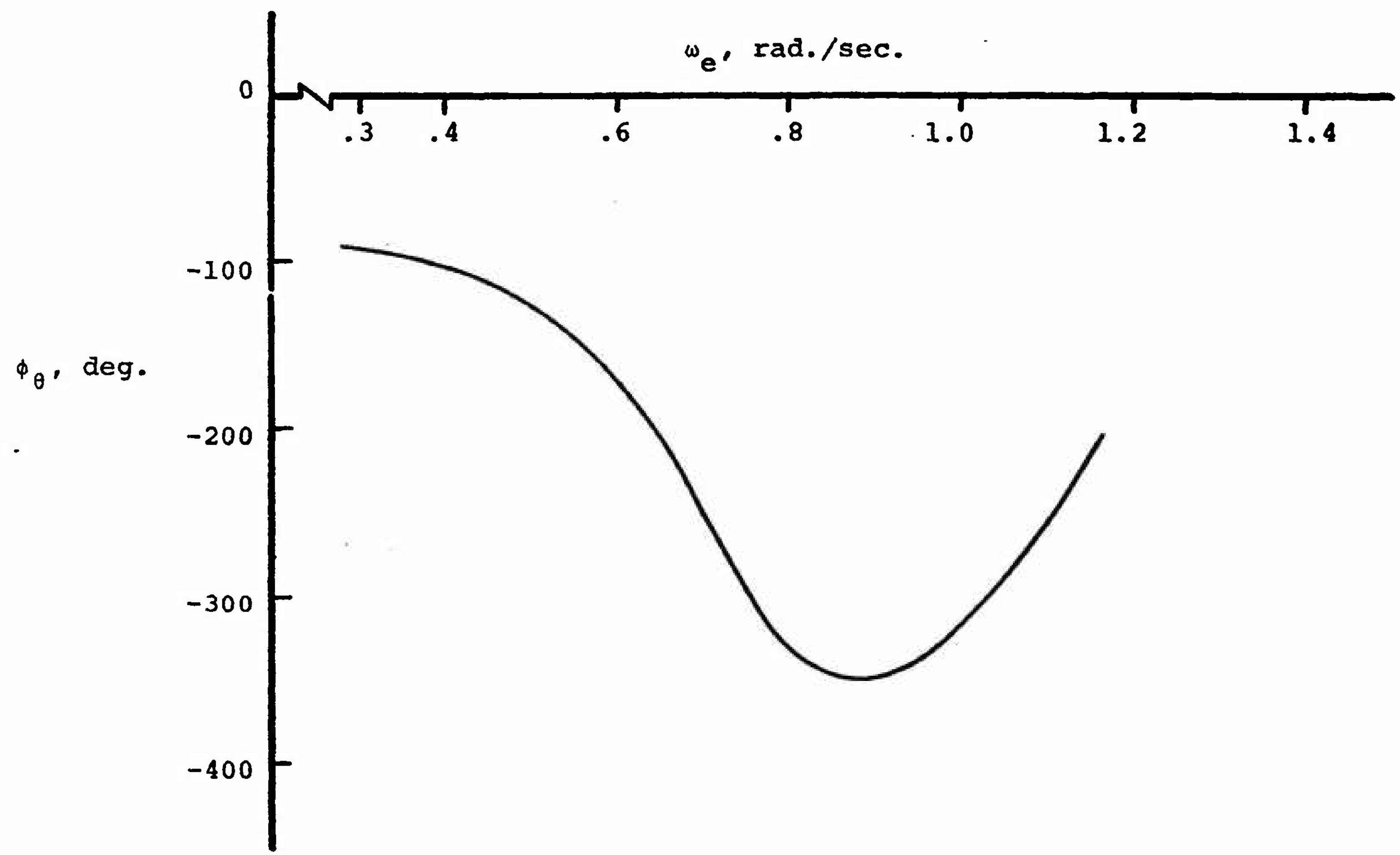

Fig. 9 Composite pitch phase frequency response, V=10 kts.

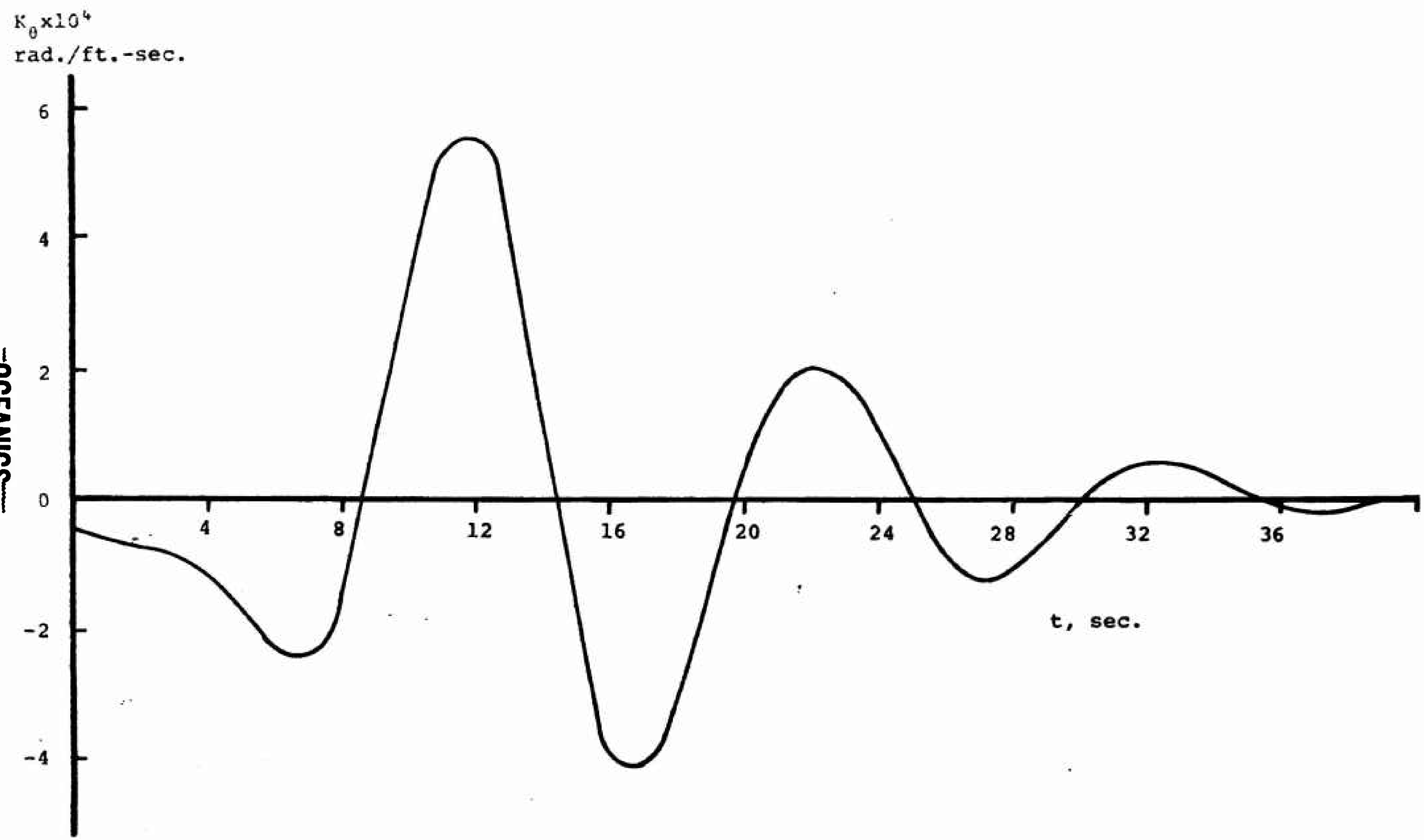

Fig. 10 Pitch kernel function, V=10 kts.

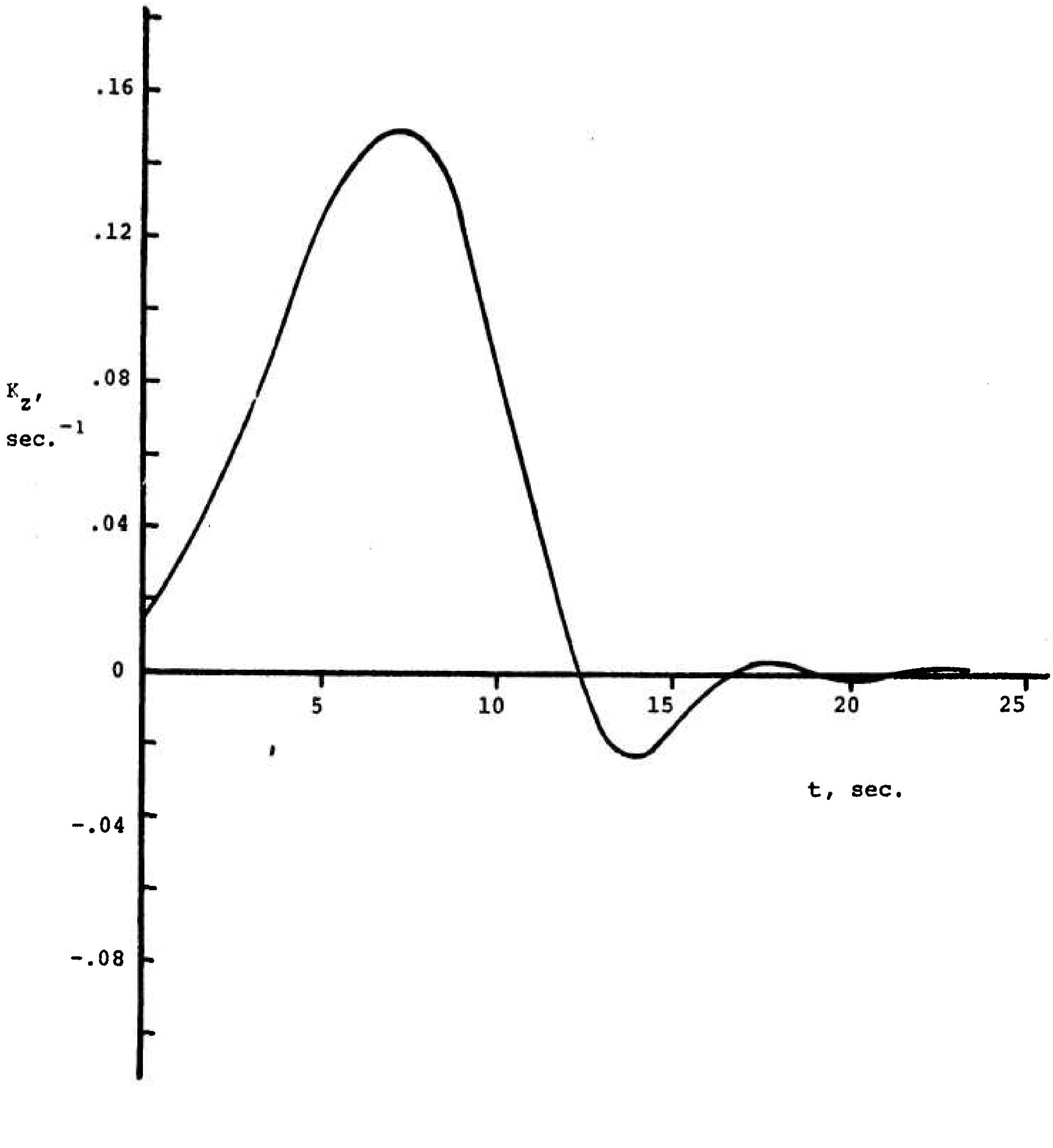

Fig. 11 Heave kernel f OCEANICS INC. =10 kts.

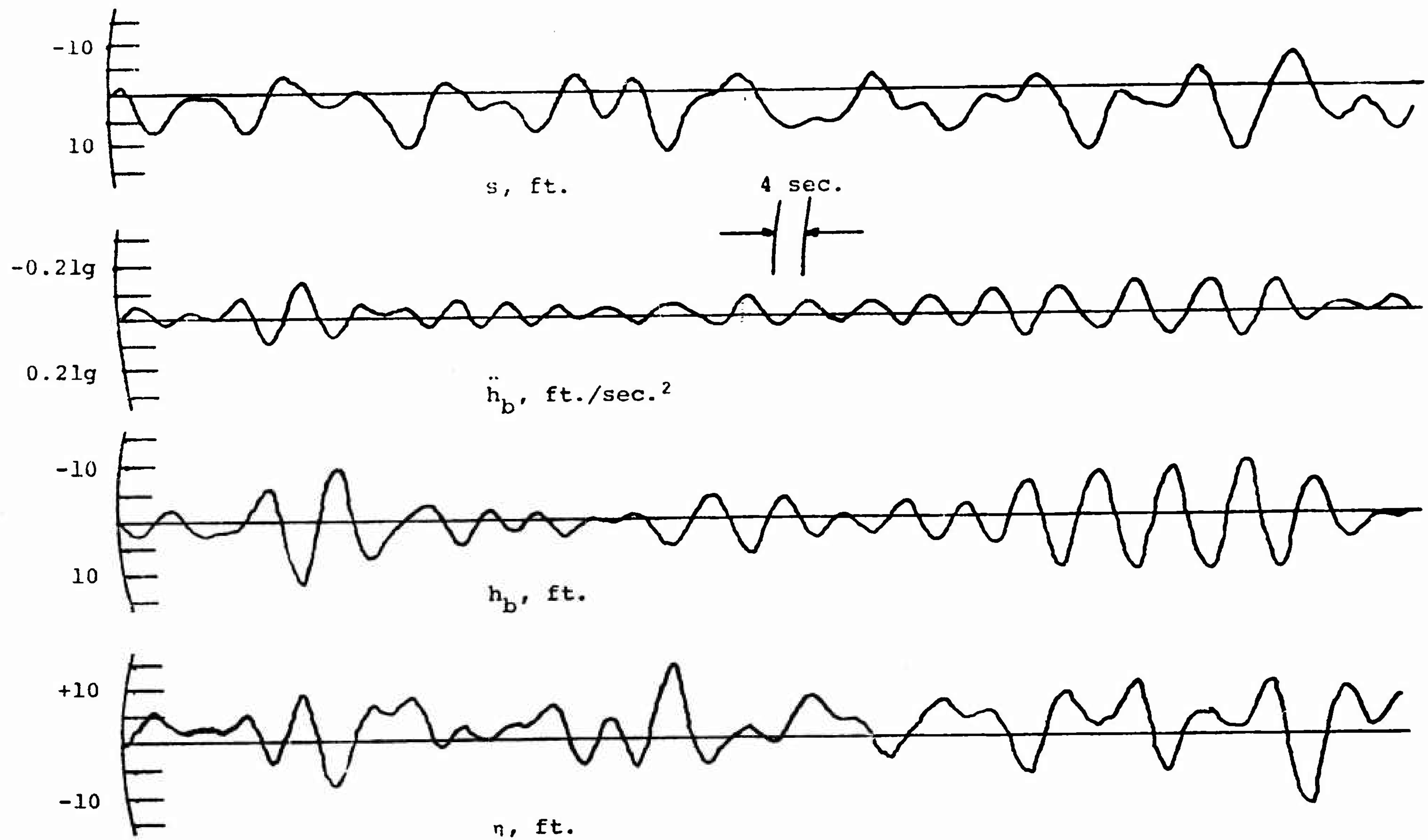

Fig. 12 Typical data recor... d results for determining wave time histories

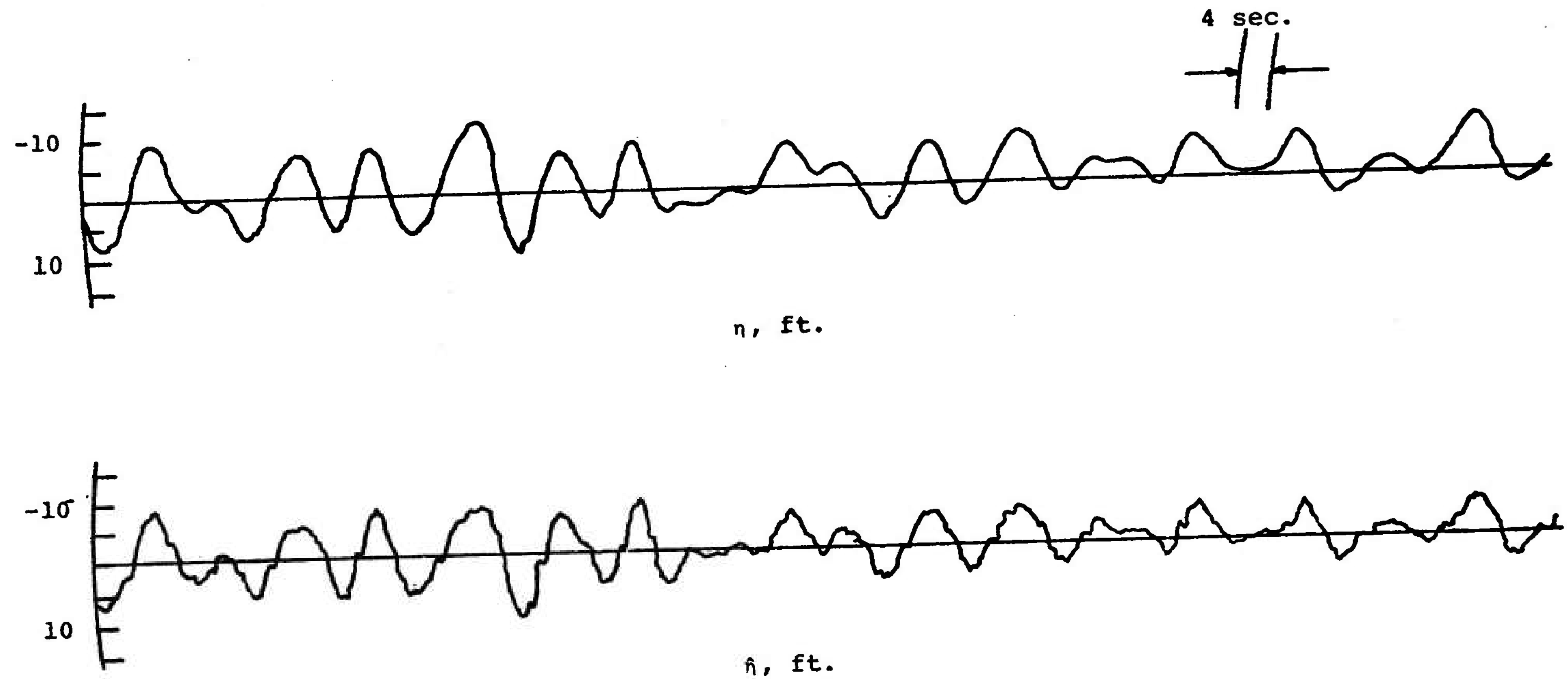

Fig. 13   Comparison of measured wave records and predicted waves, T=2 sec.

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13. ABSTRACT

The elements, both hardware and software, entering into the establishment of a system aboard ship for testing a concept for aircraft carrier deck motion prediction are described. The test procedures and results experienced in full scale evaluation are also presented. Due to lack of sufficiently severe environmental wave disturbances in some cases, as well as limited operational speed characteristics of the ship in other cases, the information obtained during the full scale tests was not suitable for proper evaluation of the motion prediction technique. The major source of difficulty encountered in the situation with sufficiently severe ocean waves was interference due to ship-generated waves, which would be overcome by having a forward speed of 10 kts. or greater. All aspects of data processing necessary in this program functioned properly, and a proposed method of wave motion prediction was shown to be successful. Further full scale testing under conditions with significant ship motions while the carrier has sufficiently high speed is recommended for complete evaluation of the prediction technique.

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